STUDIES FOR STUDENTS

RELATIONS BETWEEN CLIMATE AND TERRESTRIAL DEPOSITS—*Concluded*

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PART III. RELATIONS OF CLIMATE TO STREAM TRANSPORTATION

INTRODUCTION

It has been seen that climate exerts a primary control, only subordinate to topography, upon the rate and character of erosion on the one hand and on the other upon the chemical, structural, and organic characteristics developed in subaerial sedimentation. Between erosion and sedimentation intervenes transportation and the questions arise: To what extent is the carrying power of rivers dependent upon climate? To what degree may the ordinary stratigraphic textural variations between succeeding strata of clay, sand, and gravel be due not only to shiftings of currents and tectonic movements, but to climatic variations as well?

In a general way the influence of climate upon erosion and upon deposition is readily recognized and upon closer examination the

effects, as previously shown, are seen to be largely distinct from those which the topographic conditions alone can produce. The determination of the lithologic characters due to the climatic conditions of erosion and of deposition constitute therefore two more or less independent lines of evidence as to the climatic conditions of origin. With transportation, however, it is different. Any particular capacity for transportation is conditioned upon topography as well as climate and any change in the size or quantity of the material transported, even if due to climatic change, may conceivably be due also either to a lateral shifting of river currents, if on a small scale, or to some crustal movement if the changes occur on a greater. The proof of the climatic change must, therefore, depend primarily upon the nature of the erosion and deposition, but it will be argued in the course of this article that great climatic changes may result in transportative variations of such magnitude that the results become the most pronounced of the three divisions of climatic influence upon fluviatile sedimentation, and have sometimes been ascribed to tectonic revolutions.

For these reasons (because of the dependence of the proof of the climatic change upon the initial and final conditions of sedimentation, and also because of the great importance of such climatic change upon the power of transportation, and the resulting coarseness and thickness of the formation) this middle factor in the conditions governing fluviatile sedimentation is treated the last of the three and not in what at first sight might appear to be its more logical position.

Effects of Stream Transportation

LABORATORY EXPERIMENTS AND LAWS OF RIVER ACTION

The effect of transportation upon both the chemical and mechanical character of the material has been studied experimentally by Daubrée[1] who found upon submitting fresh and angular fragments of feldspar to prolonged trituration in the presence of distilled water that a very notable degree of decomposition was effected, as was shown by the presence in the water of silicate of potash which rendered the water alkaline.[2] The recent work of Cushman and Hubbard

[1] *Géologie expérimentale* (1879), pp. 248–88.

[2] *Op. cit.*, p. 271.

further shows that the decomposition occurring while undergoing abrasion due to movement in water takes place under exceptionally favorable circumstances, since if the initial film of decomposition is not continually removed the action of the water rapidly slows down;[1] and furthermore that the water alone, where the clogging films are continually removed, is well able thoroughly to decompose feldspar without the intervention of acid.[2] To the extent then to which mechanical abrasion occurs during river transportation decomposition is also favored and takes place at a vastly more rapid rate than in the normal weathering, which however persists through a far longer time while the material, owing to the lowering of the surface of erosion, is passing from the solid rock through the zone of soil. As to the mechanical effects:

In the series of experiments already referred to, Professor Daubrée made fragments of granite and quartz to slide over each other in a hollow cylinder partially filled with water, and rotating on its axis with a mean velocity of 0.80 to 1 metre in a second. He found that after the first 25 kilometres (about $15\frac{1}{2}$ English miles) the angular fragemnts of granite had lost $\frac{4}{10}$ of their weight while in the same distance fragments already well rounded had not lost more than $\frac{1}{100}$ to $\frac{1}{400}$. The fragments rounded by this journey of 25 kilometres in a cylinder could not be distinguished either in form or in general aspect from the natural detritus of a river-bed. A second product of these experiments was an extremely fine impalpable mud, which remained suspended in the water several days after the cessation of the movement. During the production of this fine sediment, the water, even though cold, was found in a day or two to have acted chemically upon the granite fragments. After a journey of 160 kilometres, 3 kilogrammes (about $6\frac{1}{2}$ lb. avoirdupois) yielded 3.3 grammes (about 50 grains) of soluble salts, consisting chiefly of silicate of potash. A third product was an extremely fine angular sand consisting almost wholly of quartz, with scarcely any feldspar, nearly the whole of the latter mineral having passed into the state of clay. The sand-grains, as they are continually pushed onward over each other upon the bottom of a river, become rounded as the larger pebbles do. But a limit is placed to this attrition by the size and specific gravity of the grains. As a rule, the smaller particles suffer proportionately less loss than the larger, since the friction on the bottom varies directly as the weight and therefore as the cube of the diameter, while the surface exposed to attrition varies as the square of the diameter. Mr. Sorby, in calling attention to this relation, remarks that a grain $\frac{1}{10}$ of an inch in diameter would be worn ten times as much as one $\frac{1}{100}$ of an inch in diameter, and

1 "The Decomposition of the Feldspars," *U. S. Dept. of Agriculture, Office of Public Roads, Bull. No. 28*, 1907, p. 10.

2 *Op. cit.*, p. 14.

a pebble 1 inch in diameter would be worn relatively more by being drifted a few hundred yards than a sand-grain $\frac{1}{1000}$ of an inch in diameter would be by being drifted for a hundred miles. So long as particles are borne along in suspension, they will not abrade each other, but remain angular. Professor Daubrée found that the milky tint of the Rhine at Strasburg in the months of July and August was due, not to mud, but to a fine angular sand (with grains about $\frac{1}{20}$ millimetre in diameter) which constitutes $\frac{2}{100000}$ of the total weight of water. Yet this sand had travelled in a rapidly flowing, tumultuous river from the Swiss mountains, and had been tossed over waterfalls and rapids in its journey. He ascertained also that sand-grains with a mean diameter of $\frac{1}{10}$ mm. will float in feebly agitated water; so that all sand of finer grain must remain angular. The same observer noticed that sand composed of grains with a mean diameter of $\frac{1}{2}$ mm. and carried along by water moving at a rate of 1 metre per second is rounded, and loses about $\frac{1}{10000}$ of its weight in every kilometre travelled.[1]

It is to be concluded from these statements that long transportation by reducing the size of the coarser fragments and dissolving much of the soluble matter tends to cause the material derived from mountainous regions or sub-arid climates finally to approach the chemical and mechanical nature of the waste derived from topographically gentler or climatically more humid regions. This conclusion is confirmed by observation of the beds of rivers.

Walther shows that the large rivers carry very different sediment in the different portions of their courses.

In the upper course the deposits show a complete assemblage of all kinds of rocks and minerals found within the reach of the river system. In the middle course the pebbles disappear, but the sand is still of various kinds and contains besides the original constituents, contributions from the neighboring streams. The first materials to disappear are those minerals soluble or readily disintegrated, but hardness is also important in exercising a selective action, since in the rubbing of stones together the softer are soon destroyed. In the upper course of the Avisio a great quantity of limestone pebbles may be detected between blocks of porphyry and syenite. In the lower valley, however, the limestone pebbles completely disappear and the eruptive rocks increase relatively in number. Consequently in the erosion of a mountain consisting of a schistose formation containing secondary quartz veins the entire matrix may by the transportation be transformed into fine clay and the quartz pebbles alone remain as the indestructible residue.[2]

Walther further states that

it may be directly observed upon the bed of the Rhine that sand and small fragments will be moved forwards several decimeters while a larger fragment lying

[1] A. Geikie, *Textbook of Geology*, 1903, pp. 496, 497.

[2] Translated from *Einleitung in die Geologie* (1893–94), p. 758.

in the same place will only be moved a few centimeters and therefore remains behind. Such unceasingly repeated shoving must necessarily lead to a classification along the stream course of the rolled material according to its size. So soon as the volume of a stream is altered through climatic change or tectonic movement the boundaries are immediately shifted to which large or small pebbles, sand, or clay are carried and laid down.[1]

Chamberlin and Salisbury[2] state that:

> Under certain circumstances, a stream may overload itself. Thus if a stream loaded with coarse detritus reaches a portion of its valley where fine material is accessible in abundance, some of the velocity which is helping to carry the coarse may be used in picking up and carrying the fine. This reduces the velocity and since the stream already had all the coarse material it could carry, reduction of velocity must result in deposition. It follows that when a stream fully loaded with coarse material picks up fine, it becomes overloaded, *so far as the coarse material is concerned.*

DISCUSSION OF THE DATA REGARDING RIVER TRANSPORTATION

Preliminary inductions.—From the preceding experiments, observations, and well-founded conclusions on the characteristics of river action the following inductions may be drawn.

First, the coarse material is not usually sufficiently strong or hard to stand long transportation by rivers, quartz, chert, or quartzite most effectively resisting the wear and alone being able to withstand transportation for distances of a hundred miles or more. It has sometimes been stated that the composition of a conglomerate of vein-quartz and quartzite pebbles indicates the erosion of a deeply and thoroughly decayed regolith, all but these constituents having been previously destroyed by weathering *in situ*. It is seen, however, that such a hypothesis is not necessary, since, if rivers existed sufficiently strong in current to sweep pebbles *long distances*, the quartz and quartzite would alone survive.

Second, rivers normally carry a large amount of finer material and a small amount of coarser, due to the disintegration and decomposition of the rock before it reaches the river, as well as the inherent weakness of the partially decomposed material which does reach the river in fragments. This loading up with fine material results in a lagging behind of the coarser more than if the fine was not present.

[1] *Op. cit.*, pp. 644, 645.

[2] *Geology* (1904), Vol. I, pp. 169, 170.

At times when for any reason, for example a climatic change, the fine material becomes deficient or the river volume becomes augmented, the river with the same grade may pick up the coarse material previously laid down and transport it with comparative rapidity to a lower portion of its course.

Third, Daubrée showed that upon revolving coarse and fine rock material in a barrel the coarser fragments, after being rounded, are reduced in size very slowly, so that a journey of several hundred miles would be required to reduce a pebble of 2 inches in diameter to 1 inch diameter. This may seem at first thought contradictory to the observations on river transportation, but the explanation is doubtless as follows:—The material which is of such a size that the current, which is already partially loaded with finer detritus, is just able to move it, is only moved with a fraction of the speed of the slightly smaller material. The result is that in being moved a mile down stream it may have moved ten or fifty miles relatively to the finer detritus. In so far as the rubbing and attrition are concerned, it has accomplished a journey many times the length of the actual distance moved. This lagging of the hardest coarse material under stable river conditions will be such that the added attrition due to the lagging is able to reduce it to that slightly smaller size which may be just handled by the slightly decreased velocity of the next lower portion of the river. With all but the hardest it appears, however, as previously stated, that the pebbles go to pieces faster than is called for by the necessities of transportation, so that in the lower portions of the valley there is an abnormal proportion of fine material—material which can be carried forward by a sluggish current—with the result that the condition for equilibrium is a flattened slope.

Fourth, the slope of a graded river is known to be in delicate adjustment between the volume of water, the quantity and fineness of load. These relations briefly stated are: (1) A more voluminous stream tends to flow down the same slope with greater velocity, the frictional resistence of the bed bearing a smaller ratio to the moving force. To remain in equilibrium upon such a slope the stream must carry more waste or coarser waste. Otherwise it will tend to load up its current by cutting down in the upper part of its course, building up in its lower until the grade is flattened, the velocity diminished and

equilibrium attained. The volume varies throughout the year and it is observed that in accordance with this principle by far the greater proportion of river detritus is moved in the seasons of flood. The same principle may be extended to apply to climatic cycles longer than that due to the revolution of the earth about the sun. (2) If through any climatic or tectonic change the forces of erosion are quickened and either a coarser or larger load of waste is poured into a stream of postulated constant volume, the stream must deposit the coarser of this material in place until the grade is steepened and the velocity consequently quickened sufficiently for transportation of a larger proportion. If the waste, on the contrary, becomes finer in grain or deficient in quantity, the stream responds by beginning to erode in its upper portions, tending to reach a new state of equilibrium by partially increasing its load and partly flattening its grade.

Relations of Stable Climates to Transportation

Deductive Conclusions with Confirmatory Illustrations

From the foregoing principles the relations, stated deductively, may be drawn between transportation and climate. The conclusions may then be tested by the examination of various regions which supply the requisite conditions. In sub-arid climates the streams in their upper portions have great temporary volumes and carrying power but the volume does not normally increase on the way. The result is that on escaping from the mountains the rivers in such climates are peculiarly liable to lay down a portion of their load, building piedmont slopes. The methods of erosion in an arid climate and the sudden tumultuous action of the streams result moreover in a large proportion of the deposit, consisting of a coarse and rather undecomposed waste, requiring relatively steep grades for its removal. The silt is swept farther out upon the flatter plains, while the clay and loess-like material may be carried to the front of the delta, provided the river waters are not absorbed on the way. The rivers of Argentina flowing eastward from the Andes furnish excellent examples, and to a lesser degree the rivers crossing the Great Plains of the United States. In both cases a condition of equilibrium is approached though never quite attained, between volume and waste upon a slope

which descends several thousand feet in a distance of several hundred miles.

The streams of a rainy climate on the other hand have greater carrying power over their lower and flatter courses, owing to the continually augmented volume with distance from source. The material carried is also more largely fine-grained than in the case of the sub-arid climate, a considerable portion consisting of true clay. There is consequently less tendency to build piedmont slopes and more to deliver the waste to the delta and the sea. In warm humid climates thoroughly oxidized and leached clays form a maximum percentage in the land waste, giving a river grade of maximum flatness after escaping from the mountains. The Amazon furnishes an excellent example, its bed being but 370 feet in elevation at the junction of the Marañon and Ucayali at a distance of about 1,800 miles from the ocean. The grade of the Amazon is doubtless, however, somewhat flatter and lower in its middle course than is called for by the present relations of volume and waste, since it is characterized by braided streams, distributaries, and shallow lakes. In cold rainy climates frost becomes a powerful disintegrating agent in mountainous regions, developing with great rapidity vertical cliffs skirted by coarse talus slopes and accentuating during the early portion of the cycle the steepness and roughness characteristic of such regions. The waste supplied to the rivers is coarser than that from a warmer region possessing the same broad topographic features, and the river consequently must flow on a somewhat steeper grade for the same volumetric relation of river water to sediment.

Effects of Varying Climates upon Transportation

In short streams of steep grade, such as those draining from the coast chains of California toward the ocean; or in longer ones of low grade, such as most of those of the Atlantic coast of the United States, the deposits of alluvium under all circumstances are largely marine and the chief effect of a change of climate upon the sedimentation is due to the resultant changes in the rate and kind of erosion rather than changes in the transportation. As pointed out under the subject of *the relation of topography and climate to erosion* this alone should lead to well marked differences in the sediment. In the larger

and longer river systems, however, especially those rising in mountain regions, influences of another character come in, of even greater stratigraphic importance.

CLIMATIC CHANGE FROM SEMI-ARID TO RAINY

To appreciate the maximum possible results imagine semi-arid alluvial plains such as the Pampas of Argentina and the High Plains of the United States to become the seats of a markedly rainy climate such as that of the Amazon basin. The rivers, constantly swelling in volume from additional drainage in crossing the inclined plains will erode the unconsolidated or semi-consolidated sands and gravels with immense rapidity, possibly sweeping such deposits entirely away and channeling into the rock formations below. In the case of the slopes cited from 500 to 1,000 feet of deposits could on a conservative estimate be swept off from large areas before the river currents would become sufficiently sluggish in consequence of the lowered grade of their middle courses to cease from the vigorous erosion. In the meantime over the headwaters erosion would not have increased in any such measure and might in some instances actually decrease in rate, since the vegetation if more luxuriant would hold the soil to the slopes on the one hand and on the other the corrasion of stream channels is measured by the volume of the occasional heavy floods rather than by the quantity of the constant rains. The increased fineness of the mountain waste, even if the same in quantity, and its less ratio to the greater volume of water will give the rivers still greater powers of erosion after escaping from the mountains.

In the normal topographic cycle the rivers which in their youthful stage build up piedmont slopes will in maturity begin to trench and remove them, owing to the decreased height in the region of the headwaters and the lessened rate of erosion. A strong climatic change from semi-arid to pluvial will therefore work with the normal topographic cycle and the results as recorded in the sedimentation over the lower portion of the system will be proportionately more marked than if the climatic change acted alone.

In this rapid erosion the coarse material constituting the piedmont slope will not be slowly rolled forward while being worn down *pari passu* by the friction of the smaller particles swept past, but will be

carried forward rapidly whenever reached by the tumultuous currents. It will therefore have moved relatively to the adjacent finer material but little farther than the actual distance; whereas, as previously pointed out, the coarser material usually moves relatively many times farther than the finer. Not only, therefore, will the final region of deposit undergo a sudden increase in sedimentation which may be called a veritable flood of waste, but it will be of phenomenal coarseness compared to that which preceded and that which will come after, the preceding sediment being fine in the delta region on account of the small carrying power of the rivers of the semi-arid plains; the succeeding sediment being fine because of the graded character of the mountain slopes and the more decomposed nature of the waste which they give to the streams in a time of more pluvial climate. The coarser material deposited on the delta region will, however, be finer than that previously deposited on the piedmont slopes since attrition and wear are inevitable during transportation. Such a climatic change from subarid to rainy will thus be marked by a shifting of the stored waste of the earlier epoch from the middle to the lowest portion of the river system. If it be assumed that the area of deposition in the second case is no larger than in the first, the amount will form a deposit on the average of equal thickness to the depth of the erosion in the piedmont plains. Thus it is within the limits of past possibilities that widespread sand or conglomerate formations intercalated between others of markedly different nature should be formed upon delta surfaces or over the bottoms of shallow seas, as the result of a rapid and profound climatic change. Such formations in the regions of their greater coarseness would be remarkably clean from clay and where reaching a maximum development might be several hundred or even a thousand feet in thickness. This possibility will become a probability in proportion as such arenaceous or conglomeratic formations are widespread, dissociated from the other evidences of origin through crustal movement, and correlated on other lines of evidence with climatic changes of the proper nature.

The most favorable period for the testing of these deductive statements is the Pleistocene, since the deposits are still preserved at the surface, they can be traced to their sources in the regions of erosion and great climatic oscillations are known to have taken place. The

complication, however, is that in many regions profound crustal movements are also known to have occurred. This correlation of climate with erosion and aggradation has been made by W. D. Johnson to explain the oscillations between stream-cutting and stream-building of the Great Plains region during the Quaternary. He notes that:

> There are two possible disturbing influences which may result in transformation of the gradation plane—deformation and change of climate. But it is not necessary, in order to account for change in behavior of the traversing streams, to appeal to deformation. A sufficient cause may be looked for in change of climate. There is record of erosion, with reversal to deposition and rebuilding, and reversal again finally to erosion, and there is reason for believing that this series of interruptions of the gradation cycle was an effect of climatic oscillation rather than of earth movement. The date of the building of the great débris sheet, so far as included fossil remains would seem to determine it, might range anywhere from middle Tertiary to early Pleistocene. However, the beginning of the final and present degradation stage, during which the smoothness of the Great Plains has been in large part destroyed and their surface lowered, with exception of the sod-covered plateaus of the central zone, doubtless dates from the opening of that period of climatic oscillations in the Pleistocene which, in the Great Basin region of Utah and Nevada, gave rise to repeated floodings of large areas and the creation of lakes. Indeed, it is not unlikely that the grading of certain of the minor plateau surfaces of the High Plains, which stand appreciably below the general level, is to be correlated with the several returns in the Great Basin to severe desert conditions during this period, which also are plainly recorded among the old lake evidences.[1]

In investigations of Pleistocene geology great attention is properly paid to the surface form, and in fluviatile and pluvial work erosion is more studied than sedimentation. In more distant geological times, however, it is the record of the deposits which must be almost entirely the basis of study. For such purposes, therefore, the relations of erosion and aggradation within the High Plains are not of so much final importance as the question, What was the nature of the deposit made by the erosion of the sands and gravels of the High Plains during times of wetter and colder climate? The suggested but not demonstrated answer is, that the landward edge of the corresponding deposit appears to be the Orange Sand Delta of Hilgard, now known as a Mississippian portion of the Lafayette formation.

[1] The High Plains and Their Utilization. *21st Ann. Rept.*, U. S. Geol. Survey, Pt. IV, 1901, p. 626, 628–30.

As shown by Hilgard,[1] this is a widespread, flood-made formation, extending along the great valley of the continent, the Mississippi, south of its junction with the Missouri and on the Gulf Coast reaching from Mobile Bay in Alabama to the Sabine River on the borders of Texas. The formation consists in large part of orange, rust colored, but sometimes purplish, white, or variegated sand, consisting almost entirely of quartz grains much rounded and smoothly polished, and very commonly encrusted with the rusty pigment. Near the great river channels, notably that of the Mississippi on either side, on the Tombigbee and Tennessee, as well as on the Sabine there is a steady increase of gravel. The beds are irregularly stratified, sometimes structureless for 20 feet of thickness, but have generally the flow-and-plunge structure. Hilgard considers that the formation as a whole is the outcome of fresh water in the state of violent flow. The "Orange Sand" increases in thickness toward the Gulf. In an artesian well near the Calcasieu River, 200 miles west of New Orleans, beds referred to the Lafayette are found to extend to a depth of 450 feet, beneath 160 feet of clay of the Port Hudson group; and at New Orleans the gravels have been found by borings to extend to 760 feet below the level of the sea. Hilgard showed that it overlaid the Grand Gulf beds and was in its turn covered by the Port Hudson or Columbia. He considers that it is latest Tertiary or earliest Quaternary, and he correlates this increase of fresh-water action with the melting and retreat of the first glacial stage. Chamberlin and Salisbury consider, however, that glacio-fluvial work is not concerned in the origin of this Mississippi portion, since upon careful search neither was able to find any pebbles referable to glacial action,[2] this origin being restricted to the Natchez formation which overlies it.[3] These authors favor the hypothesis that the Appalachian portions at least were developed by successive shiftings of river deposits toward the sea during Pliocene upward bowing of the partially developed Tertiary peneplain in the region of the Appalachians, but

[1] "The Age and Origin of the Lafayette Formation," *Amer. Journal of Science*, Vol. XLIII (1892), pp. 389–402.

[2] T. C. Chamberlin, "Some Additional Evidences Bearing on the Interval between the Glacial Epochs," *Bulletin of the Geological Society of America*, Vol. I, 1890, p. 470.

[3] *Geology*, Vol. III (1906), p. 308.

also recognize the influence which changes in precipitation and temperature may have had upon the rate of erosion.[1] Such shiftings of the gravels as were produced by the bowing would result in a progressively younger age of deposits found in going down the streams from the axis of bowing and therefore the Lafayette deposits of separated districts may not be of strictly contemporaneous origin.

As facts which have a bearing upon the relative influences of tectonic and climatic causes, it may be pointed out that according to Hershey erosion following a Pliocene uplift opened out basin valleys in the Ozark Highland from 75 to 100 and even 300 feet below the main Tertiary peneplain. These valleys are *floored* with Lafayette gravels which Hershey states represent the *end* (italics introduced) of deposition of the Lafayette formation, but the evidence for the latter statement is not given.[2] Following the development of these valleys another uplift, reaching in southern Missouri to at least several hundred feet, enabled the streams to excavate the inner canyon valleys of Ozarkian age. In this locality, then, the Lafayette appears to have been deposited at a time of crustal stability between two stages of uplift. While its presence could be explained by either a tectonic or climatic hypothesis, the latter is perhaps the easier, since at a time of crustal stability a climatic instability, by varying the ratio of erosion to transportation, could make itself most readily felt; now by an excess of erosion depositing material near the headwaters and steepening the grade, again by an excess of transporting power shifting the same to a lower portion of its course. Such a climatic instability marked the close of the Tertiary and increased in intensity until it resulted in the tremendous climatic reversals from glacial to interglacial intervals which marked the Pleistocene.

The chief criticisms which may be brought against this view lie in the entire lack of glacial material in the composition of the Lafayette formation and the good evidence of nearly related crustal movements of greater or lesser magnitude which affected the continent at about this time. But in continental interiors it is only land warpings

[1] *Op. cit.*, pp. 305–8.

[2] "Peneplains of the Ozark Highland," *American Geologist*, Vol. XXVII, 1901, pp. 33, 41.

which can directly influence the rate of erosion unless the land uplift is sufficiently prolonged for the streams to steepen their grades from the sea backward to the headwaters, while glacial material would be absent until the increasing ice sheets actually invaded the headwaters of the streams building the formations. In the present connection it is desired to bring into more prominence the climatic factor, but without presuming to decide upon the relative importance in this case of the tectonic and climatic causes, as a final decision must be based upon broad field-work with both hypotheses in mind. It may be pointed out, however, that this quickening in erosion and transportation appears to have been very extensive over the United States and has been ascribed to a time of cool moist climate by a number of writers from several lines of evidence, such as the included bog deposits;[1] but there is also a suggestion by Chamberlin and Salisbury, from the oxidized character of the formation, that there were effective dry seasons.[2] This might simply imply, however, a more diversified climate while at the same time more rainy. A somewhat similar paradox is pointed out by Chamberlin and Salisbury in regard to the relationship of the loess to the Iowan ice invasion and the absence of gravel trains, "both phenomena, perhaps, implying aridity, strange as that may seem in a glacial epoch."[3]

In view of the diversity of opinion upon the origin, age, and extent of the Lafayette, an opinion in the present connection should be expressed with caution. It would seem, however, that the great development of sand and gravel on the margins of the Gulf and to a lesser extent up the Mississippi River corresponds with such an erosion of piedmont sands and gravels as is seen to have taken place from the High Plains. In each case there is the added volume of water required in the one region for erosion, in the other for the transportation of such material. Both events are known to have occurred near the close of the Tertiary or early opening of the Quaternary, and by correlating the two the necessity is avoided, either of assigning the flood waters to the melting and retreat of the ice sheet, or to a greater southward slope to the Mississippi Valley, or to local tilting of the High Plains in order to rejuvenate erosion. The climatic

[1] Hilgard, *op. cit.*, p. 401.

[2] *Op. cit.*, Vol. III, p. 304.

[3] *Op. cit.*, Vol. III, p. 412.

change which is known to have taken place at about that time seems a sufficient hypothesis, and renders the other necessary only where warping or tilting of previous base levels can be demonstrated. In graded rivers of considerable volume a slight increase of volume, by producing erosion along the whole stream course would seem competent to sweep sand and gravel to great distances, which previously could not be transported along the bottom, resulting in the deposit of hundreds of feet of gravels at New Orleans whither now the Mississippi carries chiefly clay and in its channel nothing coarser than sand.[1]

On the other hand, W. J. McGee points out that the Lafayette bordering the continent was laid down during an epoch of land subsidence and that these Quaternary gravels may therefore be reworked Lafayette gravels, owing to a Quaternary land elevation and rapid erosion in the lower portions of the rivers.[2] To account for the original Lafayette gravels of the lower Mississippi, carried seaward during a low stand of the land, a hypothesis of climatic change appears to the present writer to apply most readily. If the Quaternary gravels consist, however, of a redeposition during a low stand of the sea and not during a local and progressive subsidence of the lower Mississippi, then such a fluctuating sea level is sufficient to account for a Quaternary redeposition without invoking as a further aid a climatic cause, even if such may have been also in operation.

Irrespective as to whether or not, however, the orange sand of the Mississippi Valley is the formation which represents in part the prod-

[1] Since the above was written two further communications have appeared bearing upon the age and mode of origin of the "Lafayette beds" of Louisiana. G. D. Harris records the existence of sands, clays, and gravels, the latter of typical Lafayette type, extending to a depth of at least 1,500 feet; while a Quaternary molluscan fauna extends down to about 2,000 feet. The well records thus seem to indicate that the seaward continuation of the gravels in the central portion of Louisiana as well as in those states to the east and west are rather Quaternary than Pliocene. It would seem, then, that Hilgard's views as to the contemporaneousness and interrelationship of the coarse "Orange sands" in the south and the ice sheets in the north may prove correct in spite of the fact that certain "Lafayette" gravels are said to lie beneath glacial till farther north. (G. D. Harris, "Note on the 'Lafayette Beds' of Louisiana," *Science*, N. S., Vol. XXVII, 1908, p. 351.)

[2] *Science*, N. S., Vol. XXVII, 1908, p. 472.

uct of the erosion of the High Plains, the fact still remains that the erosion was concentrated into certain stages and that somewhere sediments of increased volume and coarser nature must have been deposited.

The same principles may be applied to the more distant past. Where the sediments by the chemical conditions of erosion and deposition give evidence of profound climatic change, such for instance as ushers in glacial periods, equally profound textural changes in regions beyond the reach of glaciation, whereby sand or even pebbles were swept to the delta regions or the seas beyond, may properly be ascribed to the change of climate and do not necessarily require any crustal movement for their origin, though they may be complicated by the presence of such movements. In this way periods of glaciation may make their existence felt far beyond the actual limits of the ice invasion. It is thought by the writer that the Pottsville conglomerate or Millstone grit which so commonly underlies the coal measures of the eastern United States and western Europe, sharply separating the Carboniferous from the sub-Carboniferous of those regions, owes its origin primarily to such climatic change.

CLIMATIC CHANGE FROM RAINY TO SEMI-ARID

Having given the previous analytical discussion, the reverse side of the problem may more briefly be stated. At a time of marked change from rainy to semi-arid the waste poured into the upper part of the streams may be rapidly increased in amount and in coarseness, owing to less efficient vegetation and more concentrated floods. In crossing the plains of the middle course, however, the rivers will diminish instead of gaining in volume. They will find their previous valleys much below grade with the result that a larger proportion of river sediment will be deposited upon the piedmont slopes than would even be the case under the same climate after the river grades had acquired slopes in equilibrium with the conditions. An accentuated deficiency of sediment will consequently be noted at the terminus of the river system. The stratigraphic effect of such a climatic change will depend, as in the previous instance, upon the quickness and amount of the change, the distance of the headwaters from the delta, and the height of the source. These factors measure the difference

in angle between the stable grades under the two conditions and the volume of sediments required to be shifted to cause one grade to pass into the other.

These deductive statements find perhaps their best illustration in Persia, a region which, while so arid as to have no outflowing drainage, yet is known from several lines of evidence to have undergone marked climatic desiccation during historical times. Blanford in 1873 called attention to the superficial gravels, sands, and clays of the valleys and deserts of Persia.[1] He notes that the margins of the valleys usually consist of a long slope composed of gravel and bowlders, and with a surface inclination of from 1° to 3°. Such slopes often extend for a distance of from 5 to 10 miles from the base of the hills bounding the plains, the difference in level between the top and bottom of the incline being frequently from 1000 to 2000 feet, or even more. The peculiarity of these slopes in Persia consists in their great breadth and in the enormous mass of detrital deposits which they contain. In the central portions of the valleys the surface usually consists of very fine, pale-colored, rather sandy earth, not unfrequently impregnated with salts.[2] In discussing the origin of these gravel deposits Blanford notes that it is usually the drier tracts in which accumulations of gravel attain their greatest dimensions while

Toward Shirâz the slopes of loose detritus on the sides of valleys are much less extensive, and in places, as in the valley of the Bandamir, above Persepolis, entirely wanting,the flat alluvium of the valley extending to the limestone ranges on each side. This may be due to a former extension of the existing salt lakes far into the valleys of Shirâz and Persepolis, and to the deposition of silt in the lakes in sufficient quantities to conceal any accumulation of detritus near the side of the valley; but there appeared to me to be a similar deficiency of gravel slopes on the sides of the higher valleys containing running streams, and I am much inclined to believe that their absence is connected with the heavier rainfall. . . . .

Probable origin of gravel accumulations.—This gives a clue to the origin of these immense spreads of recent or sub-recent deposits; and in connection with the last observations I may mention that usually, in Southern Asia, so far as I have seen, it is the drier tracts in which accumulations of gravel attain their greatest dimensions. . . . . Bearing in mind that all accumulations of detrital matter

[1] W. T. Blanford, "On the Nature and Probable Origin of the Superficial Deposits in the Valleys and Deserts of Central Persia," *Quarterly Journal of the Geological Society of London*, Vol. XXIX, 1873, pp. 493, 503.

[2] *Loc. cit.*, pp. 495, 496.

are due to arrest of motion, whether partial or total, in the transporting agent, we can easily understand that the rainfall on the Persian hills may suffice to wash down as far as the sides of the valleys those fragments which, by chemical agency or the action of frost, are loosened from the hill-sides; but when once the momentum given by the steepness of the incline is at an end, the quantity of water drained from the surface is insufficient to transport the débris to a lower level; all that it can do is to leave the detritus in a long slope, the surface of which is arranged by the wash of rain.[1]

These views receive further support from the observations of Medlicott and Blanford on the relations to the rainfall of the piedmont gravels which face the south slopes of the Himalayas. In this connection they state:

Bhábar is the slope of gravel along the foot of the Himalayas. Compared with the slopes in the dry regions of Central Asia, Tibet, Turkestan, Persia, etc., the gravel deposits at the foot of the great Indian ranges are insignificant, the difference in height between the top and bottom of the slope nowhere exceeding 1,000 feet. . . . . This difference is probably partly due to the much greater rainfall in India, and to streams being consequently able to carry away a much larger proportion of the detritus washed from the surface of the hills, partly also to the circumstance that the rocks in the lower regions of the hills are not subjected to the loosening effects of frost.

The *bhábar* slope of gravel along the foot of the Himalayas, although evidently of comparatively recent formation, has frequently, to the eastward, been cut into terraces by the streams from the hills. This is a necessary consequence of the streams cutting deeper channels in the rocks of the hilly ground. It is curious to note, however, that to the westward the *bhábar* is being raised instead of being cut through by streams. The difference is not improbably due to the much greater rainfall to the eastward, and to the streams being consequently able to carry away the gravel as they cut back their bed in the rock, whereas weaker streams are prevented from cutting back their channels by their inability to wash away the gravel they have already deposited. It may be, too, that from local causes the gravels to the westward are more easily percolated by water and therefore streams, instead of carrying away the *bhábar* deposits, sink into them; but, judging from the enormous development of the gravel slopes in regions of small rainfall, it is more probable that the first hypothesis is correct.[2]

In conclusion on this topic it is to be pointed out and emphasized that *the climatic significance of gravel deposits on piedmont slopes is precisely opposite in character to the same when found on the delta plain.* Climatic inferences cannot therefore be safely made unless,

[1] *Loc. cit.*, p. 498.

[2] Medlicott and Blanford, *Geology of India* (1879), Part I, pp. 403, 412, 413.

after the exclusion of the possibility of a tectonic origin, the synchronous relations of erosion and deposition are investigated for the three portions of the river system and the relative location of portions undergoing degradation and aggradation are determined. Even by those who have recognized the frequent climatic origin of changes in river grade the necessity of clearly stating these relations seems to have escaped attention.

CLIMATIC CHANGES DUE CHIEFLY TO TEMPERATURE

In the discussion of the relations of climate to erosion the characteristics of weathering in hot and cold climates were discussed. Under the present topic of the relations of climate to transportation it need only be said that a cooler climate, by producing less evaporation, will alone serve to increase the percentage run-off of the river systems. A change from a temperate to a rigorous climate tends, therefore, not only to increase the amount of waste given to the river in its upper portion, but will result to some extent in an increase of the coarseness and quantity of material carried through to the delta. A change from a temperate to a hot climate on the other hand will tend to diminish the percentage of run-off, and with it the coarseness of the waste which is transported. Provided that the waste becomes finer, however, from greater decomposition, the quantity carried by the stream may not be decreased. At the headwaters the amount of waste is presumably increased by more intense insolation or more rapid decomposition over the conditions of a milder climate, tending to build piedmont slopes.

Oscillations to climatic extremes of any sort may, therefore, be considered to accelerate rock destruction, but only oscillations toward a more concentrated or voluminous rainfall or toward marked coolness of climate will result over the regions of distant deltas and epicontinental seas, in an increased quantity or coarseness of deposit.

CONCLUSION

CONGLOMERATES AND SANDSTONES OF MARINE, TECTONIC, AND CLIMATIC ORIGIN

Summing up the preceding discussion it is to be concluded that conglomerates and sandstone formations intercalated between others of different nature may be due to three distinct causes:

First, marine conglomerates and sandstones.—Due to marine planation and transportation, enabled to reach wide horizontal extent over shallow seas through crustal movements shifting the zone of wave and current action.

Second, tectonic conglomerates and sandstones.—Due to subaerial erosion owing to a steepening of the river slopes, either from mountain making, crustal warping, or subsidence of the ocean level.

Third, climatic conglomerates and sandstones.—Due to climatic change without necessarily any new accompanying crustal deformation. In distant periods, when the change has been of such a nature that the accumulations of gravel and sand were local and deposited near the sources of the material there is less probability, on account of the smaller original area and its higher level of deposition, of such being observed, or separated and distinguished from deposits of purely tectonic origin made by erosion during a period of stable climate. When the change was of such a nature, however, either to a more rainy or colder climate, that the pebbly or arenaceous detritus was swept forward for hundreds of miles from previous sources of erosion and accumulation, formations which may be described as great sandstone plates must have resulted, intercalated between others of a finer and more argillaceous nature, conspicuous in the geologic column both from their areal extent and their physical contrast; a contrast due to the climatic change operating in the region of deposition as well as influencing the character of the transportation. Applying this principle to the geologic past, if the sections made by nature across the deposits of ancient deltas or shallow seas indicate a periodical fluctuation in kind and in coarseness of sediment, and if such variations can be correlated *on other grounds* with climatic changes of the proper nature, it is the simpler hypothesis to hold that the latter and not repeated synchronous deformations have been the causes of the changes in sedimentation.

In the history of geologic science it is to be noted that to marine action was once ascribed the greater part of planation of the land and the formation of conglomerates and sandstones from the débris; a natural stage in geologic theory, when it is considered that the earth science developed most largely upon the northwestern shores of Europe where there is a maximum of coast line, of coastal erosion, and of shallow sea. An awakened appreciation, however, by the following

generation, of the importance of repeated epeirogenic and orogenic movements in maintaining the land surface and supplying, through subaerial erosion and fluviatile transportation, the materials of the sedimentary rocks, has led to the recognition of the tectonic causes of many of the changes which distinguish and separate the series of sedimentary formations. But it is probable that tectonic causes have been too freely ascribed in explanation of the origin of formation differences in so far as a possible climatic origin has not been held in mind. An inspection of geological literature indicates that, although the possibility of such climatic causes has been increasingly appreciated in recent years by certain investigators, yet in general, geologists have not considered the possible effects of climatic changes when seeking the causes of variations in strata, especially such as are due to size of particles. Usually the climatic factor is only regarded when considering the characteristics of the fossil fauna and flora or when deposits are present of such obvious nature as those of salt and gypsum or the products of glacial action. It is desired here to call attention to climatic change as a cause of sedimentary variation in detrital deposits of co-ordinate importance with marine planation and crustal movement. In order to discriminate correctly between the three classes of deposits where occurring in the geologic record criteria must be employed for their separation, though it is doubtless true that a correct evaluation of the factors entering into the formation of many deposits may never be achieved.

It is natural that the influence of climatic change in producing shiftings of the sedimentary facies should be the last kind of action to reach a true appreciation. Marine and tectonic conglomerates and sandstones are now observed in the making, but the *shifting* of these regions of deposition through climatic changes and by which climatic deposits as distinct from the others are to be determined is only evident on comparing the present relations of erosion and deposition with those occurring in the recent past under the same tectonic but different climatic conditions.

In conclusion something may be said of the relations of the three classes of deposits to each other. The geologic environment of a land consists of three fundamental factors: the relations of land and sea, the relations of topography, and the relations of climate. Each of these may be practically stable for a time, being subject to minor oscillations

only, but ultimately great changes take place separating earth history into its periods and eras and giving to each an individual character.

Marine conglomerates and sandstones, but especially conglomerates restricted to those whose material is obtained and sorted by the waves and transported by bottom currents, where widely developed and intercalated between unlike formations, are indicative of broad movements of the beach line; that is, of the changing relations of land and sea.

Tectonic conglomerates and sandstones are of subaerial origin and result from vertical earth movements, ultimately from either horizontal or vertical forces. To separate them sharply from climatic conglomerates and sandstones, the climate is supposed to be unchanging during the progress of the following erosion.

Climatic conglomerates and sandstones are also of subaerial and fluviatile origin, but owe their contrasts with the superior and inferior formations to climatic and not tectonic changes. To separate them clearly from deposits of tectonic origin earth movements must be supposed quiescent while climatic variations of greater or less degree are supposed to occur, resulting in changes of the sedimentary facies and in shiftings of the regions of deposit of that land waste which arises primarily through the contest of tectonic and atmospheric forces. Where the climatic changes have been great and rapid, the nature of the erosion may be so changed and the regions of deposit so widely shifted that these climatic variations may be the cause of the most striking differences between formations. Climatic conglomerates and sandstones are here made distinct and independent from those of tectonic origin by the taxonomic elevation of the *shifting location* of deposits (in space) to co-ordinate importance with *intermittent uplift* and resulting pulses of erosion (in time).

Changes in volume of ocean waters, earth movements, and atmospheric activities are the three mixed and fundamental causes by which the three classes of deposits become possible, but the records which they embody are largely distinct and independent. By separating conglomerates and sandstones into these three classes the sedimentary rocks, therefore, present a threefold record, the marine conglomerates giving that of the variable relations of land and sea; the tectonic conglomerates, the record of variable vertical uplifts; the climatic conglomerates, the record of variable temperature and rainfall.